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NONLINEAR OPTICS IN THIN FILMS

G.I. Stegeman
C.T. Seaton

Optical Sciences Center
University of Arizona
Tucson, AZ 85721

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This technical report has been reviewed and is approved for publication.

Christopher M. Clayton

CHRISTOPHER M. CLAYTON, PhD
Project Officer

FOR THE COMMANDER

LEE P. SCHELONKA
Captain, USAF
Chief, Quantum Optics Branch

HARRO ACKERMANN
Lt Col, USAF
Chief, Optics Division

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Two nonlinear phenomena with the potential for locking together two waveguides/lasers have been examined theoretically.

Phase conjugation of a plane-wave incident field onto a waveguide supporting two guided pump beams is a potentially useful phenomenon. This process can be very power efficient because of the strong spatial confinement of the pump beams. Multi-reflection effects within the guiding film lead to oscillations in the signal with increasing waveguide thickness and incidence angle.

Coupling between two waveguides can be achieved by the exchange of spatial solitons when a self-focusing medium is used between two parallel waveguides. Model calculations based on the powerful Beam Propagation Method have indicated transfer efficiencies as large as 80 percent.

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INTRODUCTION

The objective, scope, and technical effort for this program, as stated in the contract STATEMENT OF WORK, were:

1.0 *Objective.* The objective of this work is to develop a theoretical description for nonlinear guided-wave degenerate four-wave mixing.

2.0 *Scope.* The effort will consist of theoretical investigations of the nonlinear properties of nonlinear waveguides. The studies will include the investigation of four-wave mixing.

4.0 *Technical Effort.* The contractor shall review the existing theory for nonlinear waveguides including soliton-based nonlinear guided-wave phenomena. The contractor shall develop a theoretical description and assessment for degenerate four-wave mixing in nonlinear waveguides.

The first phase of the program consisted of reviewing the literature on the two problems of interest to this contract, namely

1. degenerate four-wave mixing in waveguides.
2. soliton transfer between waveguides.

The second phase of the program consisted of original theoretical calculations on both of the above problems.

REVIEW OF DEGENERATE FOUR-WAVE MIXING IN WAVEGUIDES

Degenerate four-wave mixing (DFWM) in fiber and planar waveguides has been discussed theoretically and demonstrated experimentally. Previous work in this area, up to early 1986, is summarized in Ref. 1. In the case of fibers, all of the truly original work was done before 1983. This waveguide system is of marginal interest since the interacting beams must travel along the fiber axis; that is, fibers correspond to a one-dimensional system. The possibilities for working in planar waveguides are much more diverse because the interacting beams can either lie in the plane of the film, or be incident onto it from above or below. Therefore, in this report, we concentrate on degenerate four-wave mixing in planar waveguide structures.

There are essentially three viable geometries for performing degenerate four-wave mixing in planar waveguides:

1. All four waves guided.
2. Two externally incident pump beams, and guided probe and conjugate beams.

3. Two guided pump beams, and external probe and signal beams.

The first case, all four waves guided, has been analyzed by at least two groups, ourselves included.[2,3] In fact, two experiments have been reported.[4,5] The first used the nonlinear material carbon disulphide as the cover material above the guiding film. Because the fraction of power guided in the cover medium is small, the efficiency for this geometry was low. In the second experiment, the waveguide itself consisted of the nonlinear medium, namely semiconductor-doped glass, and the efficiencies were very good. For peak powers of tens of watts, efficiencies of 10% have been achieved with picosecond pulses. It is because the guided beams are strongly confined in one dimension that the reflectivities per unit input power for the pump beams are large. However, for a guided wave, the phase information can be coded in only one dimension; that is, along the wavefront, perpendicular to the propagation direction.

The geometry with two external pump waves, incident from above and below the guiding film, and a guided probe beam leading to a guided-wave signal beam has also been treated theoretically.[6] However, the applications of such a geometry are not obvious.

The geometry which best utilizes guided waves for phase conjugation is the third. As illustrated in Fig. 1, the contra-propagating pump beams are guided, meaning that small total powers are required to obtain high waveguide intensities. The probe beam is incident from above the waveguide and a phase conjugate signal is obtained both on reflection and transmission through the waveguide. This particular case has been neither analyzed nor demonstrated experimentally. This case is treated theoretically in the next section.

DEGENERATE FOUR-WAVE MIXING WITH GUIDED PUMP BEAMS

The geometry shown in Fig. 1 was analyzed in the weak conjugate signal limit. The counter-propagating pump beams are both assumed to be TE_0 guided waves; that is, the electric field polarization is the y-direction. (We do not treat the TM case here, although we do not expect anything to be substantially different other than the existence of a Brewster angle phenomenon.) The probe signal is incident from above the thin-film waveguide in the form of a plane wave at an angle θ_c relative to the normal. In addition to the usual reflected DFWM signal, there is also a "transmitted" DFWM signal attributable to multi-reflections inside the film.

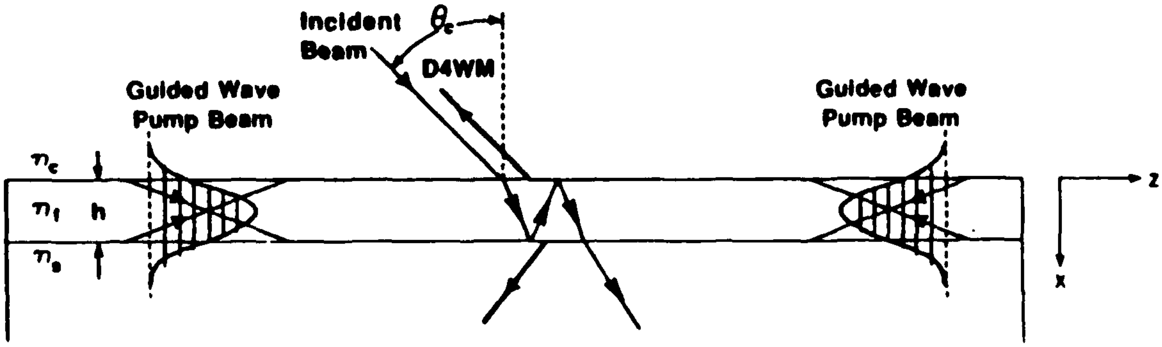

Fig. 1. The DFWM geometry analyzed here. The pump beams are guided by a film of thickness h. A plane-wave beam is incident from the cladding side and DFWM is obtained both on reflection and transmission through the film.

The calculation of the nonlinear polarization associated with the DFWM signal is relatively straightforward.[7] Including the degeneracy factor,

$$P_y^{NL}(r) = 4\epsilon_0\ n_{2E}(x)\ E_+(\omega)E_-(\omega)E_{inc}^*(\omega)\ , \tag{1}$$

where n_{2E} is defined in the usual way as a field-dependent refractive index of the form $n(|E|) = n_0 + n_{2E}|E|^2$ (and E is the local field). Here $E_+(\omega)$ and $E_-(\omega)$ are the counter-propagating pump beams, and $E_{inc}(\omega)$ is the plane-wave incident field.

The strength of the DFWM signal on reflection and transmission is calculated by solving the polarization-driven wave equation for fields with wavevector component $-\kappa_p k_0$ parallel to the surface;[7] i.e.,

$$\left[-\kappa_f^2 - \frac{1}{k_0^2}\frac{d^2}{dx^2}\right]E_y(\omega,x) = \frac{1}{\epsilon_0}\ P_y^{NL}\ . \tag{2a}$$

where

$$E_s(r,t) = \frac{1}{2}\ e_y\ E_y(\omega,x)\ e^{i(-\kappa_p k_0 z\ -\ \omega t)} + c.c\ . \tag{2b}$$

The form of the DFWM signal fields far from the film is given by

$$n_c:\ E_y(\omega,x) = D_c e^{-i\kappa_c k_0 x} \quad \text{when } x < 0\ . \tag{3a}$$

$$n_s:\ E_y(\omega,x) = D_s e^{i\kappa_s k_0(x-h)} \quad \text{when } x > h\ . \tag{3b}$$

Noting that the intensity S is given by $0.5n_0c\epsilon_0|E_y|^2$ and the (intensity) DFWM reflection and transmission coefficients are given by

$$R = \frac{S_r}{S_{inc}} = |D_c|^2 = \eta_r P_+ P_- \ . \tag{4a}$$

$$T = \frac{S_t}{S_{inc}} = \frac{n_s}{n_c}|D_s|^2 = \eta_t P_+ P_- \ . \tag{4b}$$

The details of the solutions can be found in the appended paper.[7]

Numerical calculations were performed on two representative guided-wave film geometries, both utilizing typical nonlinear organic parameters. In the first case, the following parameters were assumed: $n_c = 1.0$, $n_f = 1.6$, $n_s = 1.45$, $\lambda = 1.06$ μm, $n_{2If} = 10^{-16}$ m^2/W and $n_{2Is} = 0.0$ In the second case, the effect of a nonlinearity in the substrate instead of the film was examined, with $n_{2If} = 0.0$ and $n_{2Is} = 10^{-16}$ m^2/W. Relatively large oscillations in the DFWM cross section were observed for both cases, and two additional calculations were performed with a smaller difference between the film and substrate refractive indices, namely $n_f = 1.6$ and $n_s = 1.59$.

Figures 2 and 3 show η_r and η_t, respectively, as a function of incidence angle θ_c. For film thicknesses near waveguide cutoff, the externally incident beam does not show any resonances across the film and the variation in the cross sections η_r and η_t is smooth with angle. However, as the film thickness is increased and resonances begin to appear across the film, distinct maxima and minima in the cross section appear, their number increasing with film thickness. Since the transmitted DFWM signal requires reflection at the lower film boundary, the oscillations are much larger on transmission than on reflection. Therefore it appears feasible to optimize the signal for a given film thickness by varying the incidence angle.

The variation in η with film thickness at a 45° incident angle is shown in Fig. 4. As expected, oscillations again occur because of multi-reflections of both the incident and signal beams in the film. When the index difference between the film and substrate is reduced, the amplitude of the oscillations is also reduced, as shown in Fig. 5.

The effectiveness of using a linear film on a nonlinear substrate is examined in Fig. 6. Clearly the cross section decreases rapidly from its cutoff value and falls orders of magnitude below that obtained on reflection.

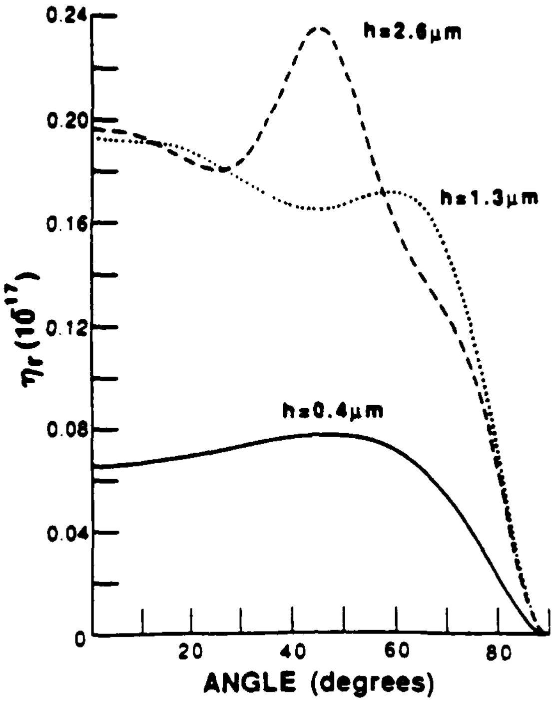

Fig. 2. The reflection DFWM cross section η_r versus angle of inidence θ_c for three different film thicknesses. Here $n_c = 1.0$, $n_f = 1.6$, $n_s = 1.45$, $n_{2lf} = 1\times10^{-16}$ m^2/W and $n_{2ls} = 0.0$

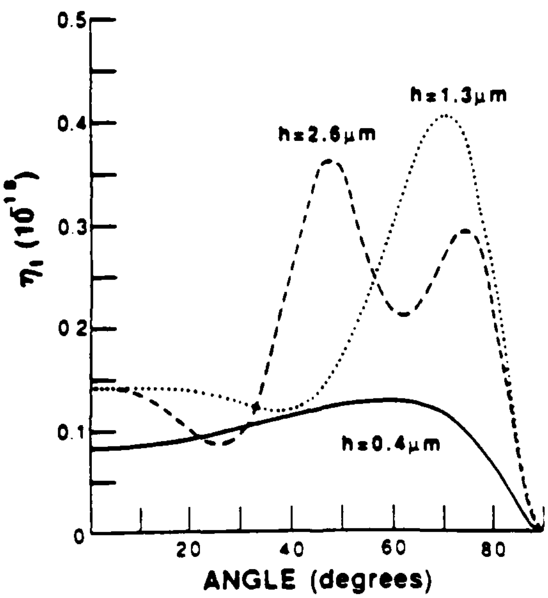

Fig. 3. The transmission DFWM cross section η_t versus angle of inidence θ_c for three different film thicknesses. Here $n_c = 1.0$, $n_f = 1.6$, $n_s = 1.45$, $n_{2lf} = 1\times10^{-16}$ m^2/W and $n_{2ls} = 0.0$

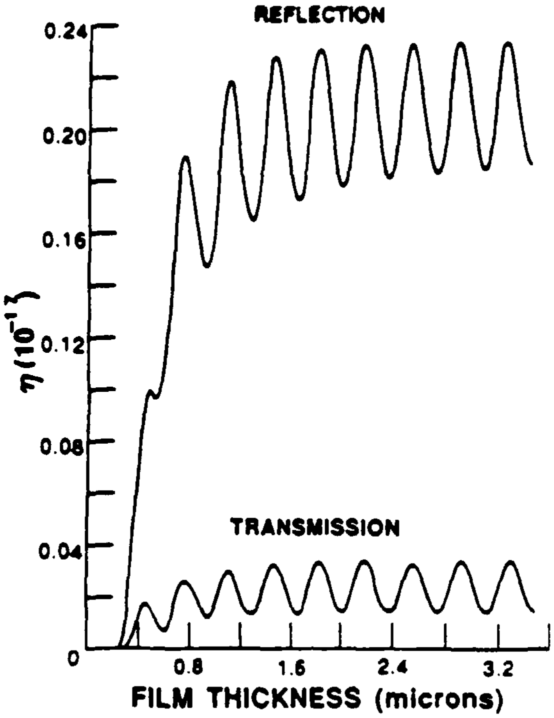

Fig. 4. The reflection (η_r) and transmission (η_t) DFWM cross sections versus film thickness for $\theta_c = 45°$. Here $n_c = 1.0$, $n_f = 1.6$, $n_s = 1.45$, $n_{21f} = 1\times10^{-16}$ m^2/W and $n_{21s} = 0.0$

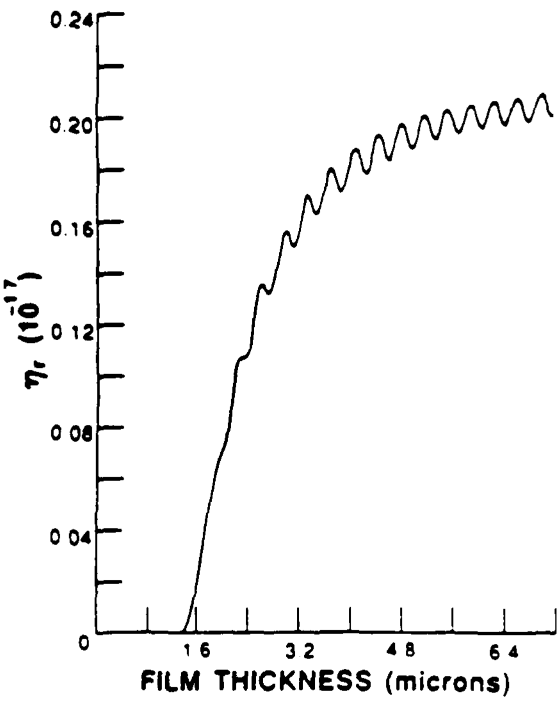

Fig. 5. The reflection (η_r) DFWM cross section versus film thickness for $\theta_c = 45°$. Here $n_c = 1.0$, $n_f = 1.6$, $n_s = 1.59$, $n_{21f} = 1\times10^{-16}$ m^2/W and $n_{21s} = 0.0$

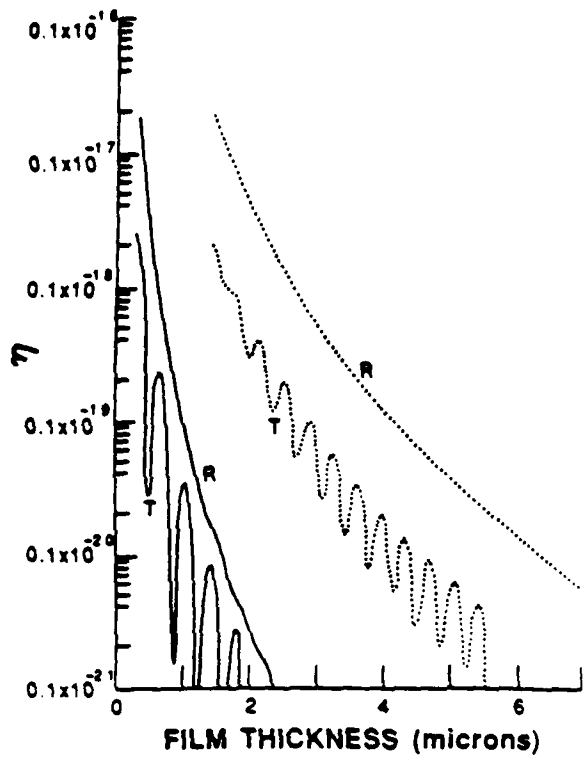

Fig. 6. The reflection ($\eta_r \equiv R$) and transmission ($\eta_t \equiv T$) DFWM cross sections versus film thickness for $\theta_c = 45^0$. For the solid line, $n_c = 1.0$, $n_f = 1.6$, $n_s = 1.45$, $n_{2Is} = 1\times10^{-16}$ m²/W and $n_{2If} = 0.0$. For the dotted line, $n_c = 1.0$, $n_f = 1.6$, $n_s = 1.59$, $n_{2Is} = 1\times10^{-16}$ m²/W and $n_{2If} = 0.0$

We now compare the detailed behavior shown in the preceding figures with an approximation based on plane-wave analysis. It is well known that for plane waves in the small signal limit,[8]

$$R = \frac{S_r}{S_{inc}} = 16\pi^2 \frac{L^2}{\lambda^2} n_{2I}^2\ S_+ S_-\ , \tag{5}$$

where $n = n_0 + n_{2I}S$ and L is the interaction distance. To a useful approximation $S_\pm = P_\pm/h_{eff}$, where h_{eff} is the effective waveguide thickness. Therefore, rewriting for the guided-wave case,

$$R = 16\pi^2\ \frac{L^2}{{h_{eff}}^2}\ \frac{n_{2I}^2}{\lambda^2}\ P_+ P_-\ , \tag{6}$$

should provide a useful approximation. For thick films, $h_{eff} \cong h \cong L$ and the cross section coefficient becomes independent of film thickness. Estimating for the present case, we obtained 0.16×10^{-17} for the cross section, in good agreement with the "average" value of the oscillations of 0.2×10^{-17} shown in Figs. 4 and 5. Despite the fact that h = L is usually good to at best ± 25%, Eq. (6) does give a useful value for the cross section. In addition, it predicts the asymptotic behavior with increasing film thickness. Furthermore, since $h_{eff} \rightarrow \infty$ at cutoff, where the substrate field degenerates into a plane wave traveling parallel to the surface, $R \rightarrow 0$ at cutoff can also be understood. Finally, it is clear that the asymptotic value of the cross section with film thickness depends primarily on the nonlinearity of the film, and not the details of the waveguiding structure.

Equations 5 and 6 also provide some insight into the maximum values of reflectivity that might be available. Assuming power densities approaching damage values, for example 10 GW/cm^2, and 1-μm-thick films, this corresponds to $P \cong 10^7$ W/m, leading to a maximum reflectivity of 0.02 (2%). (For a 1-cm guided-wave beam, a peak power of only 100 KW is required for the pump beams.) Hence, for this material system, pump-wave depletion can be ignored. For semiconductor materials (which also exhibit large absorption), reflectivities in excess of 100% should be possible.

COMMUNICATION BETWEEN WAVEGUIDES VIA SOLITON TRANSFER

One way to communicate information and enforce phase locking between two waveguides is via the transfer of energy between them. The usual way to accomplish this is to place two parallel waveguides in close proximity so that their fields overlap and energy exchange occurs with propagation distance. In the integrated optics community, such an arrangement is called the "directional coupler." Another, novel approach is to use the exchange of spatial solitons between the two waveguides. It is this approach which is examined here.

Interaction between waveguides via the exchange of spatial solitons only became a possibility about two years ago when it was shown that spatial solitons are emitted from strongly excited nonlinear waveguides.[9] In 1986, Wright et al. showed that a single waveguide with a nonlinear cover medium emitted one or more spatial solitons into the cover medium when excited too strongly. This spatial soliton travels away from the waveguide at an angle which increases with increasing incident power. The question posed then was whether a second, parallel waveguide could trap a reasonable fraction of the spatial soliton emitted from the first guide. This possibility was the impetus for the research described in this section. Clearly, as a minimum requirement, the spacer region between two guiding films must contain a self-focusing nonlinearity for spatial solitons to exist between the two waveguides.

The approach used is the Beam Propagation Method (BPM). Each linear guide in the geometry shown in Fig. 7 is defined by a refractive index step Δn superimposed on a background substrate index n_0. This involves solving numerically for the total field envelope E(x,z) using the slowly varying phase and amplitude equation[10]

$$\left[\frac{\partial^2}{dx^2} + \frac{\partial^2}{dz^2} + 2in_0\frac{\partial}{\partial z} + (n^2(x,|E(x,z)|^2) - n_0^2)\right] E(x,z) = 0\ , \tag{7}$$

where all of the spatial dimensions are scaled to $k_0(\omega/c)$. The refractive index distribution $n^2(x,|E(x,z)|^2)$ consists of two parts: the first is the linear index distribution as described above, and the second is the nonlinear part, which is written as $\alpha(x)|E(x,z)|^2$. Equation 7 was solved numerically using up to 4096 transverse grid points.[10]

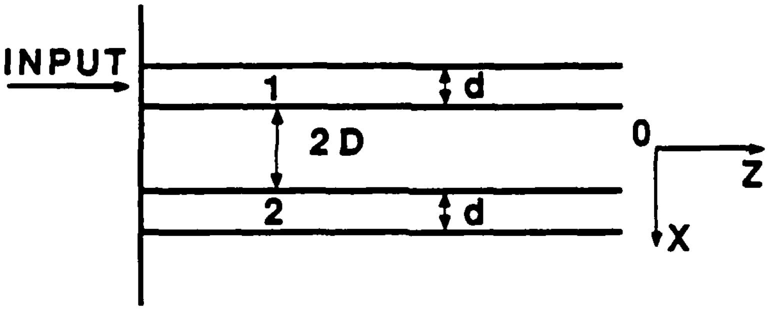

Fig. 7. Geometry of the soliton coupler. Normalized parameter values used are d = 16, D = 22, n_0 = 1.55, Γn = 0.02, and α_0 = 1. Guide 1 is the input guide.

Using an effective-particle-theory approach, the conditions on $\alpha(x)$ for effective trapping of the solitons in the second waveguide were deduced. A useful geometry is to have self-focusing nonlinearities both in the region between the two waveguides, and in the second film. Figure 8 shows the transmitted flux through the input guide (guide 1, Figure 8a) and the parallel guide (guide 2, Figure 8b) as a function of input flux into guide 1. Transmission of 100% in guide 1 occurs, followed by a sharp threshold beyond which soliton emission from guide 1 occurs. In comparison, no energy is transmitted into guide 2 below the critical flux for emission of solitons from guide 1, but just above a significant fraction (≅80%) of the input energy is transferred to guide 2. Figure 8 clearly shows an extremely sharp switching characteristic which is due to the fact that soliton emission is a threshold effect. It is also interesting to note that the energy transferred to guide 2 stays fairly constant above the switch point, indicating some limiting action.

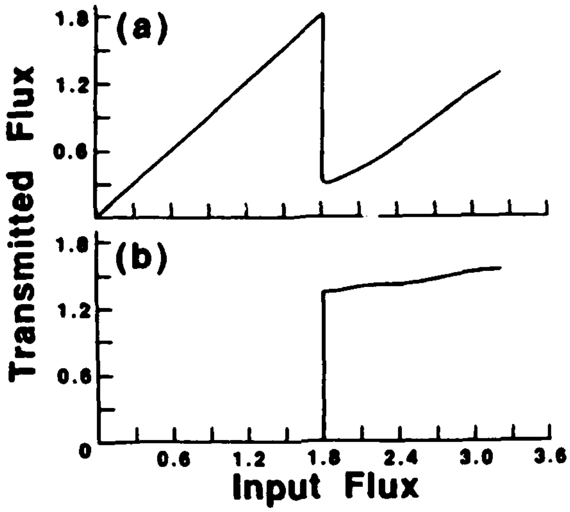

Fig. 8. Transmitted flux versus input flux for (a) guide 1, and (b) guide 2.

The phase characteristics of the transferred guided wave have not yet been analyzed. However, it appears that the system may be quite noisy. For example, the BPM results for the energy as a function of transverse and propagation coordinates are shown in Fig. 9. Immediately after transfer between the two waveguides, the field distributions undergo oscillations which do not damp out for many hundreds of wavelengths of propagation.

SUMMARY

We have examined theoretically two nonlinear phenomena with the potential for locking together two waveguides/lasers.

Clearly, phase conjugation of a plane-wave incident field onto a waveguide supporting two guided pump beams is a potentially useful phenomenon. This process can be very power efficient because of the strong spatial confinement of the pump beams. Multi-reflection effects within the guiding film lead to oscillations in the signal with increasing waveguide thickness and incidence angle.

Coupling between two waveguides can be achieved by the exchange of spatial solitons when a self-focusing medium is used between two parallel waveguides. Model calculations based on the powerful Beam Propagation Method have indicated transfer efficiencies as large as 80%.

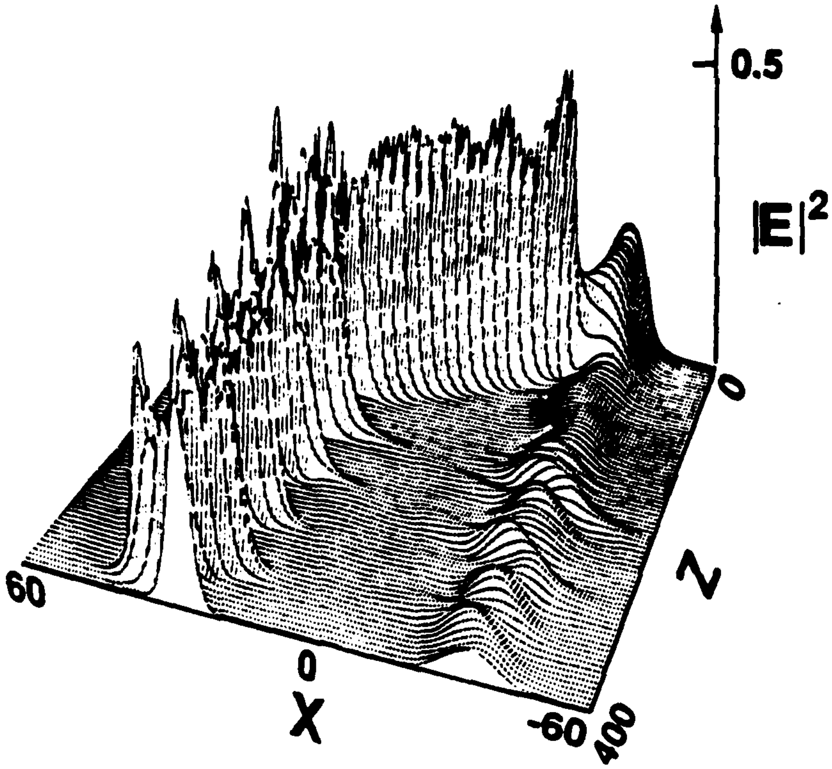

Fig. 9. Evolution of the intensity profile in a soliton coupler for $S_{in} = 2.25$. *The longitudinal coordinate is z in units of free-space wavelengths.*

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1. "Degenerate four-wave mixing from a waveguide with guided pump beams," G. I. Stegeman, E. M. Wright, and C. T. Seaton, submitted to J. Appl. Phys.

2. "Soliton coupler," D. R. Heatley, E. M. Wright, and G. I. Stegeman, submitted to Appl. Phys. Lett.

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